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Evaluation of non-fumigant alternatives to methyl bromide for weed control and crop yield in California strawberries (*Fragaria ananassa* L.)

Jayesh B. Samtani[a], Husein A. Ajwa[a], John B. Weber[a], Gregory T. Browne[b], Susanne Klose[a], Jonathan Hunzie[a], Steven A. Fennimore[a,*]

[a] Department of Plant Sciences, University of California-Davis, 1636 East Alisal St., Salinas, CA 93905, USA
[b] USDA-ARS, University of California-Davis, One Shields Ave., Davis, CA 95616, USA

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ABSTRACT

In California, USA, agricultural fumigant use regulations hinder the complete transition from methyl bromide (MB) to alternative fumigants. Alternative fumigants such as 1,3-dichloropropene (1,3-D) and chloropicrin (Pic) are being used on approximately half of California conventional strawberry production fields. Geographic use limits and buffer zones set by the California Department of Pesticide Regulation for 1,3-D + Pic restrict a more complete replacement of MB. Due to the regulatory constraints and public resistance to fumigant use, it is necessary to develop fumigant-free strawberry production systems. Trials were conducted during the 2007/2008 and 2008/2009 strawberry growing seasons at Salinas and Watsonville, California. Non-fumigant treatments including steam, mustard seed meal (MSM), *Muscodor albus*, and furfural, fertilizers including Mustard Products & Technologies fertilizer and stabilised urea, and fungicide treatments including AG3(NP), fludioxonil + mefenoxam (mfx), and mfx + thiophanate-methyl were evaluated for weed control and strawberry fruit yield, and compared to MB + Pic (MBPic) standard soil fumigation and an untreated control. Steam treatment applied pre-plant to achieve soil temperature of ≥70 °C for 20 min up to 25 cm soil depth consistently provided weed control similar to the MBPic standard soil fumigation. Use of oxyfluorfen herbicide prior to fungicide applications in 2008/2009 also controlled weeds similar to the MBPic standard soil fumigation. Strawberry yields in steam-treated plots with the exception of steam alone in 2007/2008 at Salinas, were comparable to MBPic. At Watsonville in 2008/2009, treatment effect on strawberry yields was insignificant. Yields in furfural and MSM treatments were comparable to MBPic only in some years or sites. With the exception of steam, none of the treatments can be considered viable replacement to MB.

1. Introduction

Methyl bromide (MB) and chloropicrin (Pic) mixtures have been the most widely used soil fumigants for California strawberry cultivation since the 1960's (Wilhelm and Paulus, 1980). Under the Montreal Protocol, regular use of MB ended in the USA and other developed countries in 2005, and currently only critical uses of MB are permitted (USEPA, 1993). Alternative fumigants to MB including Pic, metam sodium, and 1,3-dichloropropene (1,3-D) have their advantages and disadvantages, but none have completely replaced MB (USEPA, 2009). In California, the Department of Pesticide Regulation further regulates agricultural fumigant use by mandating buffer zones for fields near residential areas and imposing township (defined as an area of 93.2 km^2) caps for fumigants such as 1,3-D, to protect the environment, and humans from harmful exposure to fumigants (Carter et al., 2005). In 2008, a 14% decline in gross revenue was estimated for California strawberry growers using alternatives in comparison to those using MB, and declining availability of MB to the growers could have an additional adverse economic impact on the $1.8 billion strawberry industry (USEPA, 2009; AgMRC, 2010). To minimize the impact of the loss of MB, and to avoid regulatory constraints and public resistance to agricultural fumigant use, we undertook research to identify effective non-fumigant treatments for strawberries in California. Identifying additional effective products and methods for pest control would help minimize the dependence on a single product.

Steam has been used since the 1880's to kill soilborne pests including fungi, weeds, nematodes, and insects (Baker and Roistacher, 1957). Steam treatments were shown to kill most plant pathogens when the soil temperature is maintained at ≥65 °C for 30 min (Baker

* Corresponding author. Tel.: +1 831 755 2896; fax: +1 831 755 2898.
E-mail address: safennimore@ucdavis.edu (S.A. Fennimore).

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and Roistacher, 1957). Glucosinolate-containing plants (e.g., *Brassicaceae*, *Capparidaceae*, *Moringaceae* spp.) have been tested as biofumigants and green manure crops (Brown and Morra, 1997). The potential has also been demonstrated for use of dehydrated plant tissues and defatted seed meal pellets derived from plants in the Brassicaceae family (Rice et al., 2007). Glucosinolates are degraded in soil by the enzyme myrosinase to D-glucose and allyl isothiocyanate. This latter product showed adverse effects on growth and survival of bacteria, fungi, insects, mammals, and weeds (Feeny and Rosenberry, 1982; Rice et al., 2007). *Muscodor albus* (*M. albus*), an endophytic fungus, was found growing in the bark of the small limbs of the cinnamon tree (*Cinnamomum zeylanicum* Breyne) in the rainforests of Central America. The fungus produces a mix of volatile compounds that effectively inhibits or kills several plant and human pathogenic fungi and bacteria, nematodes and certain insects (Strobel et al., 2001; Strobel, 2006). *M. albus* is produced commercially in California, USA, and it received conditional approval of the Environmental Protection Agency for agricultural use in the USA (Strobel, 2006). This fungus appears safe, environmentally friendly and shows potential as a mycofumigant to replace MB for soil sterilization (Strobel, 2006). Furfural (2-furancarboxaldehyde, $C_6H_4O_2$) is an aromatic aldehyde that is prepared from organic non-food residues of food crops and wood wastes via hydrolysis and later purification by distillation (Burger, 2005). It has a wide range of uses including as herbicide, insecticide and fungicide (Kirk-Othmer, 1984). Studies have shown that furfural controlled plant-parasitic nematodes without adversely affecting crop growth and yield (Rodríguez-Kábana et al., 1993; Bauske et al., 1994).

Intensive strawberry production in California requires supplemental fertilizer applications. AgroThrive (AgThr, 2.5-2.5-1.5 NPK) is an organic liquid fertilizer that supplies nutrients for plant growth, and is reported to enhance nutrient release in the soil by stimulating soil microbial activity (AgroThrive, 2010). Another specialty fertilizer, Mustard Products & Technologies (MPT) fertilizer (5-2-1 NPK and 94% organic matter) was suggested to improve fertility and physical properties of soil (MPT Inc., 2010). Stabilised urea (SUr, 24-0-0-44 Ca) is a lime nitrogen stabiliser developed as a micro fertilizer additive for commercial agriculture (Bi-En Corp, Portland, OR, USA; *personal communication*).

Fungicides are widely used in strawberry production systems to control foliar (e.g., powdery mildew, common leaf spot), root and crown (Anthracnose rot, Phytophthora crown rot), and fruit diseases (e.g., Botrytis rot, leather rot). AG3(NP) (mono- and di-potassium salts of phosphorous acid) is registered for the control of *Pythium*, *Plasmodiophora*, *Peronospora*, *Alternaria* and *Phytophthora* spp. on small fruits, berries, and other agronomic crops (Ameribrom, Inc., 2010). Fludioxonil (fdx) belongs to the phenylpyrrole class of fungicides and controls soil and foliar diseases by preventing fungal respiration (Syngenta, 2010a). In use with other fungicides such as cyprodinil, fdx effectively controls strawberry fruit rot diseases (Daugovish et al., 2009; Wedge et al., 2007). Mefenoxam (mfx) registered for use in strawberries in the USA, systemically controls diseases such as leather rot, caused by *Phytophthora cactorum* (Rebollar-Alviter et al., 2007; Syngenta, 2010b). Thiophanate-methyl (tph-m) is found to be an effective replacement for the fungicide benomyl (Mossler and Nesheim, 2009; Jordan, 1973). Tph-m is used to suppress crown rot (*Colletotrichum* spp.) and to control fruit rot (*Botrytis* spp.), powdery mildew (*Sphaerotheca* spp.) and leaf blight (*Dendrophoma* spp.) in strawberries (United Phosphorous, 2010).

Oxyfluorfen (oxyfn) can be used as a pre-emergence or post-emergence herbicide for control of weeds in various crops (Dow AgroSciences, 2009). In strawberries, oxyfn must be applied to fallow beds 30 d prior to strawberry planting (Dow AgroSciences, 2009). Oxyfn + napropamide controlled weeds resulting in 20% higher strawberry yields compared to untreated control (Gilreath and Santos, 2005). The objective of this study was to evaluate the efficacy of non-fumigant practices such as steam disinfestations, bio-based products as MSM and *M. albus*, fertilizers including MPT fertilizer and SUr, fungicide treatments as AG3(NP), fdx + mfx, and mfx + tph-m, and oxyfn herbicide for weed control, crop yield, and quality in California strawberry production systems relative to standard MBPic soil fumigation.

2. Material and methods

2.1. Site and treatment description

Trials were conducted at the USDA-ARS research facility in Salinas, CA (lat. 36° 4′N, 121° 3′W, elevation ≈ 47 m) and at Monterey Bay Academy in Watsonville, CA (lat. 36° 5′N, 121° 5′W, elevation ≈ 24 m). The soil in Salinas was a Chualar sandy loam (fine-loamy, mixed, thermic, Typic Argixerolls) with a pH of 6.5 and organic C content of 0.7%. At Watsonville, the soil was an Elder sandy loam (coarse-loamy, mixed, thermic, Cumulic Haploxerolls) with pH of 6.1 and organic C content of 0.6%. Products used in the treatments for this study and their source are listed in Table 1. In the 2007/2008 strawberry season, ten treatments were tested at the Salinas and Watsonville site, and in the 2008/2009 season, eight (Salinas site) or nine (Watsonville site) treatments were tested (Table 2).

2.2. Treatment application

Treatment plots were 1.3 m wide by 12.2 m long beds at the Salinas site, and 1.4 m wide by 12.2 m long at the Watsonville site, arranged in a randomized complete block design with four plots (replicates) per treatment at each site. Irrigation in the beds was applied via two drip tapes (Toro Ag, El Cajon, CA, USA) spaced 13 cm and 8 cm apart in Salinas and Watsonville respectively, with emitters spaced 30 cm apart and an emitter flow rate 1 L/h at 70 kPa. The drip tape was placed 25 cm (in Salinas) and 30 cm (in Watsonville) from the bed center at a soil depth ranging from 2 to 5 cm.

MBPic and furfural were applied pre-plant through the drip system in 40 mm of water. In the steam and steam + AgThr treatments, steam was generated using a Sioux steam SF-20 diesel powered generator and was applied pre-plant to the beds through flexible

Table 1
The products used in treatments applied at Salinas and Watsonville, California, and their source.

Product	Source
MBPic	Tri-Cal Inc., Hollister, CA, USA
Steam	Mobile steam generator, Sioux Corporation, Beresford, SD, USA
AgThr	AgroThrive™ LF; AgroThrive, Inc., Morgan Hill, CA, USA
MSM	Biofence; Triumph Italia, Livorno, Italy
M. albus	AgraQuest, Inc., Davis, CA, USA
Furfural	Agriguard Co. LLC, Cranford, NJ, USA
MPT fertilizer	MPT Mustard Products & Technologies, Inc., Saskatoon, Sk., Canada
SUr	STABL-N; Bi-En Corp, Portland, OR, USA
AG3(NP)	Calirus 150; Ameribrom, Inc., Fort Lee, NJ, USA
Fdx	Cannonball™; Syngenta Crop Protection Inc., Greensboro, NC, USA
Mfx	RidomilGold®, SL; Syngenta Crop Protection Inc., Greensboro, NC, USA
Oxyfn	GoalTender®; Dow Agrosciences LLC, Indianapolis, IN, USA
Tph-m	Topsin® 4.5 FL; United Phosphorous Inc., King of Prussia, PA, USA

Abbreviations. MBPic, Methyl bromide (67% MB): chloropicrin (33% Pic); AgThr, AgroThrive; MSM, mustard seed meal; *M. albus*, *Muscodor albus*; MPT, Mustard Products & Technologies; SUr, stabilised urea; fdx, fludioxonil; mfx, mefenoxam; oxyfn, oxyfluorfen; tph-m, thiophanate-methyl.